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Birth of Cosmic Microwave Backgrounds

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Abstract. Understanding the cosmic microwave background, i.e. the relic radiation from the early universe, is essential to have useful insights into the fundamental physics. This paper is an attempt to summarise the origin of this background, in a very comprehensive way for the beginners in physics.

1. Introduction

The universe we live in, is full of an almost-uniform microwave radiation coming from all directions in the sky. Presence of such radiation was originally predicted by Alpher and Herman [Alpher and Herman(1948)], 16 years before the actual experimental detection by Penzias and Wilson[Penzias and Wilson(1965)] in 1964. Known as the cosmic microwave background(CMB), these radiations are the messengers from very far past- the early universe. This paper will give a short version of the story of their birth in the post-Big Bang universe.

2. Hubble's law and the Big Bang

In 1929, Hubble discovered [Hubble(1929)] that the distant galaxies show higher redshifts than the closer ones. Hubble's observation simply imply that the galaxies are moving away from us. There could be two interpretations of this discovery- either we are at the center of the universe (which clearly violates the ′cosmological principle′†) or the universe is actually expanding itself. The second interpretation is the widely excepted one.

From his observations, Hubble found that the recessional velocity v of a galaxy is directly proportional to its distance D from the observer, i.e.

$$\mathbf{v} = H_0 \mathbf{D} \tag{1}$$

where H_0 is a proportionality constant known as Hubble's constant, or more appropriately the Hubble's parameter.

Now if everything is moving away from each other, there must have been a time in the past when everything were relatively closer. Hence, if we trace back time and dig into

† The cosmological principle, the cornerstone of any cosmological model states that, when viewed at a larger scale, the universe appears to be homogeneous and isotropic, regardless of where the observer is.

the history of the universe, eventually we would come to a point when everything were extremely close to each other- the extreme hot, dense state mathematically interpreted as the ′singularity′.

The big bang theory, in fact, states something similar- that our known universe, was in an infinitely hot and dense phase at its beginning, known as the primordial singularity. Around 13.7 billion years ago, an event of incredibly giant expansion (′the big bang′) occurred causing the ′beginning′ or ′birth′ of the universe we know. Sometimes the term ′big bang′ is also used to denote the singularity itself instead. However, we do not know where the singularity came from or what caused the big bang to occur, because the concept of time and the laws of physics we know today were invalid in that regime.

3. An Opaque Early Universe

There are several versions of big bang cosmology describing what happened in the very early era of the universe just after the big bang. Worth mentioning the popular inflationary epoch, though there are some non-inflationary cosmological models as well. The cosmic inflation (proposed by Alan Guth, 1981 [Guth(1981)]) is a period of giant exponential expansion of space started after the big bang, at a cosmic time of 10^{-36} seconds and lasted till 10^{-32} - 10^{-33} seconds. This incredible burst caused the space to expand incredibly fast, even faster than the speed of light. One popular idea is that the separation of strong and electroweak forces in the grand unification epoch (10^{-43} - 10^{-36} seconds) just before the inflation actually triggered it, and soon after the inflation ended, a huge energy was released by the decaying inflation field, known as ′reheating′. Reheating left an universe full of hot plasma of gluons and quarks, followed by the formations of various subatomic particles. Note that the universe continued expanding and cooling down even after inflation but in a much slower rate.

3 minutes after its birth, a billion degree hot universe went through the big bang nucleosynthesis- forming the earliest nuclei in the history, mainly hydrogen and helium through nuclear fusion and releasing lots of energies in forms of photons. When the universe was 20 minutes old, the temperature (millions of kelvin) was not enough for the fusion process to go on, but was still enough to energize the photons. These high energy photons frequently interacted with free electrons (Thomson scattering) in the plasma, resulting in short mean free paths of the photons and thus making the atomic bindings impossible. Hence we had a radiation dominated opaque universe that time.

4. Cosmic Microwave Background

As time passed , the universe cooled further down. Eventually, about 400,000 years after the big bang, the photons finally cooled down enough that they were no longer able to interact with the electrons via Thomson scattering. This ′photon decoupling′ allowed electrons to bind with protons and form neutral atoms(′recombination′). Soon enough, the photons acquired larger interaction mean free path and the universe became

′transparent′ for the photons or radiations. These are the photons, indeed, what we see today as cosmic microwave background. The surface of a sphere with a radius equal to the distance travelled by a photon since the ′last scattering′ at the recombination epoch is known as the ′surface of last scattering′.

A rough estimate of the temperature when the photons were decoupled could be derived from the Saha Equation. Assuming a thermal and chemical equilibrium of hydrogen, electrons and protons (and ignoring the helium†), Saha equation can be written as

$$\frac{n_e n_p}{n_H} = \frac{(2\pi kT)^{\frac{3}{2}}}{h^3}(\frac{m_e m_p}{m_H})^{\frac{3}{2}} \exp[-\frac{E_R}{kT}] \tag{2}$$

where m denotes the mass and n the number density with the subscripts e, p and H referring to protons, electrons and hydrogen atoms respectively. E_R is the ionization energy of hydrogen (13.6 eV), T the temperature and k the Boltzmann constant.

Expressing the densities in terms of n_B, the baryonic number density, the equation takes the dimensionless form

$$\frac{X_e X_p}{X_H} = \frac{8.8 \times 10^{13}}{\Omega_B h^2}(\frac{E_R}{kT})^{\frac{3}{2}} \exp[-\frac{E_R}{kT}] \tag{3}$$

The terms X known as fractional Ionizations and Ω_B is the dimensionless Baryon density parameter. Using experimental value [Fixsen(2009)] of

$$\Omega_B h^2 \approx 0.02 \tag{4}$$

where $h \equiv H_0/(100kms^{-1}Mpc^{-1})$, and assuming a 90% completed recombination process

$$\frac{X_e X_p}{X_H} = 0.9 \tag{5}$$

, eq. 3 yields $T \approx 3000K$ for the temperature of the recombination era. Note that this is just a rough estimate as we considered all electrons to combine with atoms and neglected any residual ionizations.

After the decoupling, we had a transparent universe with uninterruptedly moving photons with an energy distribution of blackbody. As the universe expanded, the temperature dropped inversely as the scale factor a†

$$T \propto \frac{1}{a(t)} \tag{7}$$

causing the early radiation to have a redshift z defined by

$$1 + z = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_0}{a(t_{em})} \tag{8}$$

† Saha equation, by Indian astrophysicist Meghnad Saha, only holds for weakly ionised plasma of a single species.

† Scale factor is a measure of the expansion rate of universe and is related to the Hubble parameter as

$$H = \frac{\dot{a}(t)}{a(t)} \tag{6}$$

where λ_{obs} is the wavelength of the radiation observed today in an universe with scale factor a_0 and λ_{em} is the wavelength when the radiation was originally emitted at some earlier time t_{em}, the scale factor being $a(t_{em})$ that time. Combining eqs. 7 and 8 gives the temperature-redshift relation

$$T_{em} = T_0(1+z) \tag{9}$$

If we use the temperature of CMB as observed today as $T = 2.725K$ and the temperature when the early photons were decoupled as $T_{em} \approx 3000K$, the redshift becomes $z \approx 1100$, causing the wavelength of early radiations today to be in the microwave band.

5. Concluding remarks

Understanding the past of the CMB is essential to unlock the physics mysteries in the present. At the beginning of the paper, we mentioned that the CMB are an ′almost-uniform′ radiation- but we never discussed why it is so. The signal actually observed by Penzias and Wilson, was indeed, apparently isotropic. But more recent measurements, such as those from Planck Surveyor show some faint anisotropies. These anisotropies are a great means to probe the primordial universe and also a firm evidence for dark matter.

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